Tuning material and component properties to reduce weight and increase blastworthiness of a notional V-hull structure

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Abstract

In this paper, concepts are investigated for tuning material properties and component configurations in order to design structures with unique dynamic characteristics for mitigating blast loads while maintaining or reducing weight. The Dynamic Response Index (DRI) is employed as an occupant injury metric for determining the effectiveness of the each blast mitigation configuration that is considered. A finite element model of a notional V-Hull structure is used as a numerical example in this study. The material properties and the configuration of the inner bulkheads that connect the V-shaped outer surface with the inner floor are used as design parameters for reducing the DRI at a typical occupant location. In this particular example, it is demonstrated that both the weight of the structure and the DRI can be reduced simultaneously. This is achieved by creating a new structural design that features energy absorbing and decoupling mechanisms among the bulkheads, floor, seat, and the occupant.

Keywords: Lightweight ground vehicle structure; Lightweighting; Blast mitigation; Blastworthiness; Energy absorption; Dynamic response index

1. Introduction

One of the main thrusts in current US Army science and technology activities is the development of occupant-centric vehicle structures that make the operation of the vehicle both comfortable and safe for the soldiers. However, increased occupant protection often comes at a cost of increased weight. Ideally, a new vehicle design would feature a lighter weight structure, because this enables faster transport, higher mobility, greater fuel conservation, higher payload capacity, and a reduced ground footprint of supporting forces. Therefore, a key design challenge for the Army is to develop occupant-centric ground vehicle structures that can provide high levels of protection against explosive threats while maintaining or reducing the total vehicle weight. Full system, end-to-end modeling and simulation methodologies [1-5] have been used extensively for the development of blastworthy ground vehicles in the Army acquisition process. More recently, reduced-order modeling approaches [6-9] have also been developed for this purpose.

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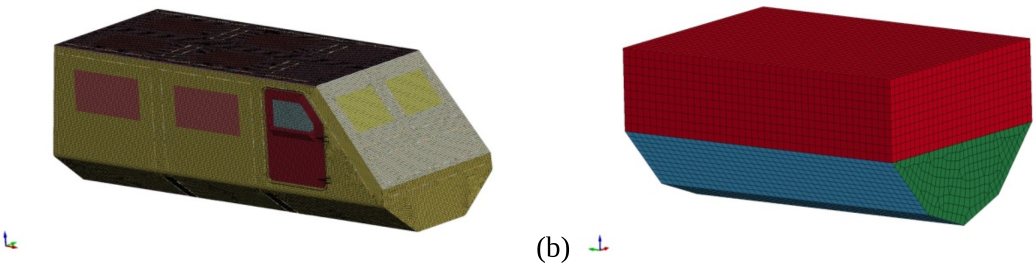
In this paper, a computational investigation is presented that examines whether the properties of the materials and/or components used in the construction of a ground vehicle structure can be effectively used as design variables to significantly improve the dynamic characteristics. More specifically, the goal of this work is to explore the possibility of tuning the material and component properties to improve the blastworthiness while simultaneously lowering the total weight of a V-hull structure.

A generic V-Hull structure developed by the US Army TARDEC, referred to as the TARDEC Generic V-Hull, [2] is used in this study as the baseline numerical model for investigating these concepts. The Dynamic Response Index (DRI), which is a standard occupant injury metric [10] for underbody blast simulations and testing, is used as a measure of the structural performance with respect to survivability. In the absence of an anthropomorphic test device in numerical models to measure lumbar loads, the DRI is the next best indicator of lumbar injury performance [11]. Furthermore, the DRI can be easily calculated from structural vehicle accelerations, [11-12] as shown in Appendix A.

In the literature, various concepts for employing the properties of certain materials as a mechanism to absorb energy have been presented. For example, utilizing shear thickening fluid due to its large capacity for energy absorption has been investigated [13-15]. Shear thickening fluid is a specific type of non-Newtonian fluid with its viscosity dependent on the strain rate. It acts like a solid when experiencing a large shear load, such as an impulse of high pressure but of short duration from a blast, and returns to liquid form when the load is removed. Employing the plastic deformation induced in material for absorbing energy has been considered for designing blast-resistant structures [16]. The failure mechanisms in unidirectional fiber-reinforced composites of delamination, fiber-matrix debonding, matrix cracking, and fiber breakage have been considered for creating blast mitigation configurations [17]. For similar purposes, functionally graded metallic materials constructed in a layered sandwich configuration with several absorption layers have been also considered [18].

In this paper, the concept of using properties of “softer” structural materials is investigated. This allows for higher deformation levels in the structure, which—in combination with a damping mechanism—can result in a reduced base excitation leading to lower DRI values and hence a decreased risk of occupant injuries. Specifically, the properties of the inner bulkheads that connect the outer V-Hull bottom to the inner floor (Figure 2(a) and 2(b)) are tuned in this manner, thereby offering an isolation mechanism that reduces the DRI metric. The main contributions of this paper are: (1) the implementation of this structural design strategy, and (2) the demonstration of its effectiveness in terms of simultaneously reducing weight and increasing blastworthiness for a numerical example of a notional, generic V-hull structure.

In the following sections of this paper, information is first presented about the numerical models employed in this study, namely the V-Hull finite element model and the DRI lumped parameter models. The commercial software LS-DYNA is used in the blast simulations, and the LS-DYNA viscoelastic material definition is used for setting the various properties of the internal bulkheads in a parametric study. Therefore, a brief discussion on the viscoelastic material definition in LS-DYNA is presented. Then, two different lumped parameter models for the DRI metric are described. In the first setup, a spring-mass model with a single degree of freedom (DOF) representing the upper torso of the occupant (see Appendix A) is mounted directly in the middle of the inner floor. In the second setup, a three-DOF model representing the upper torso of the occupant, an energy-absorbing seat, and an energy-absorbing floor (see Appendix B) is mounted to the hull. Finally, the process followed in the parametric study is discussed along with the final design configurations that reduce both the structural weight and the DRI metric simultaneously.

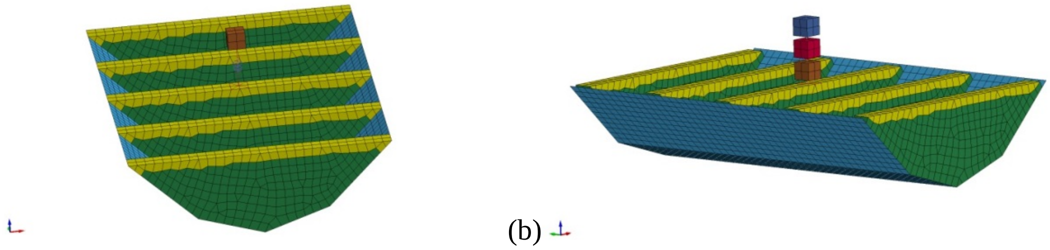


(a) (b)

Figure 1. Finite element models for two notional vehicle hulls: (a) TARDEC Generic V-Hull structure; (b) Simplified V-Hull structure that is used for the numerical results in this study.

2. Numerical models and dynamic response index (DRI)

The TARDEC Generic V-Hull structure is presented in Figure 1(a). This is a representative but notional ground vehicle structure that can be used in survivability research studies. In fact, this model was developed to be sufficiently generic that it could be used to evaluate the effectiveness of underbody blast analysis methods and blast mitigation technologies in a collaborative manner. Historically, the Army has had difficulty collaborating with industry and academia on research related to underbody blast events due to the sensitive nature of the work. Data generated from testing military vehicles typically cannot be shared with external research partners. To alleviate this issue, TARDEC has developed this generic vehicle hull model with the intent to share it with academia and industry in the hope of spurring innovation in blast analysis methods and blast mitigation technologies.



(a) (b)

Figure 2. Finite element model of the lower part of the simplified V-hull with: (a) One-DOF model for determination of DRI; (b) Three-DOF model for determination of DRI

For this work, the main dimensions and the geometry of the TARDEC Generic V-Hull were used as a basis for creating a simplified V-hull model that is shown in Figure 1(b). This simplified V-hull was used for all of the numerical results shown in this paper. The baseline model for the simplified V-hull has the same thicknesses and material properties for the main structural components as the TARDEC Generic V-Hull structure. It also contains inner bulkheads connecting the outer V-shaped surface with the inner floor, as shown in Figure 2. The material properties of the bulkheads are used as design parameters in the parametric study. The air blast loading feature in LS-DYNA (*LOAD_BLAST) is used, with the origin located 0.2 m below the bottom of the V-hull in the z (vertical) direction and directly beneath the geometric center of the hull in the x-y plane.

Figure 2(a) shows the single-DOF (SDOF) lumped parameter model connected directly to the vehicle structure to evaluate the DRI. The upper part of the structure and the inner floor are removed from the figure in order for the internal bulkheads to be visible. These and all other parts that are omitted from the figure for visualization purposes are included in the simulations. The DRI is used as a metric for assessing the safety design characteristics of a vehicle. It represents the dynamic response of the lower lumbar region of an occupant. The DRI is computed from the maximum dynamic compression measured in the spring, which is determined from the governing equations shown in Appendix A. For reference, a critical DRI value of 17.7 corresponds to a 10% chance of serious injury.

In the LS-DYNA model, a single spring-mass-damper system with a mass of 34.51 kg, a natural frequency equal to 52.9 rad/s, and damping ratio of 0.224 is attached to the finite element model of the simplified V-Hull. As mentioned earlier, a second three-DOF lumped parameter configuration is also considered, with the two intermediate DOF representing the seat and the floor. This second configuration is shown in Figure 2(b). In this case, the DRI is determined by the relative compression in the spring connecting the top and middle masses. The nonlinear spring constants and linear damping coefficients for the lowest (floor) DOF and for the middle (seat) DOF are shown in Appendix B. By including these single-DOF and three-DOF systems directly in the simulations, the calculations in the governing equations shown in Appendix A and B are automatically performed by LS-DYNA.

3. Lightweight vehicle structure design

The density, the modulus of elasticity, and the dissipation properties of the material comprising the bulkheads are used in the parametric study for reducing simultaneously the weight of the structure and the DRI. The viscoelastic material definition of LS-DYNA (MAT_061) is used for modeling this material, which models both viscous and elastic characteristics with a stress-strain relation that depends on the load history. [19] It behaves as a spring-damper system and two classical models (Maxwell's and Kelvin's) are employed in the material definition. The parameters that are considered include: mass density, bulk modulus, short-time shear modulus, long-time shear modulus, and decay constant. The bulk modulus, the short-time shear modulus, and the long-time shear modulus are determined by the instantaneous modulus of elasticity and the asymptotic modulus of elasticity. A linear relationship between the instantaneous modulus of elasticity E_0 and the asymptotic modulus of elasticity E_∞ is used, with $E_0=1000\times E_\infty$. Therefore, the Poisson's ratio of the material, the mass density, the decay constant, and the asymptotic modulus of elasticity are sufficient for defining the viscoelastic material properties. In this study, these material properties are tuned in order to create an isolation mechanism to reduce the occupant DRI while also reducing the total structural weight.

3.1 Parametric study using SDOF model

The configuration with the single-DOF DRI model connected to the floor (Figure 2(a)) for evaluating the DRI was analyzed first. In an initial parametric study, the density and the stiffness properties were changed for the entire volume of each bulkhead. Two main conclusions were drawn from this initial effort.

First, it was decided to preserve the original steel properties for the upper part of each bulkhead (colored yellow in Figure 3) and alter the stiffness, the density, and the dissipation characteristics in the remaining portion of each bulkhead (colored green in Figure 3). The reason for this approach is to avoid excessive local flexibility at the location where the SDOF model is attached to the floor when the bulkhead has reduced stiffness properties. The local flexibility at the attachment point makes it difficult to control the spring compression that determines the DRI.

The second observation was that the overall mass of the vehicle has an impact on the overall rigid body response of the vehicle and therefore on the DRI value. Four equal lumped masses were added at the four corners of the vehicle to keep the total weight constant at the typical representative weight of such a vehicle. For each configuration, the values of the lumped masses were selected in a manner that the overall mass of the vehicle remained constant. This approach also reflects the ability to increase the payload of a vehicle even when the structure itself becomes lighter. The locations where the lumped masses were attached are shown in Figure 3.

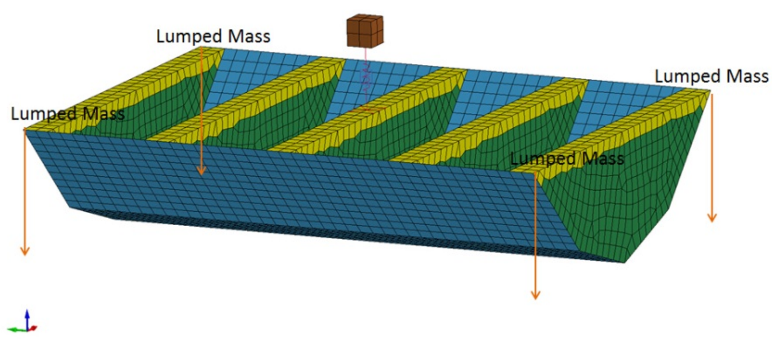


Figure 3. Partition of the bulkheads into two sections (yellow and green); and locations where lumped masses are attached for preserving the overall vehicle mass

First, an original configuration made of regular steel was tested so that the mass of the underbody explosive yields a DRI value that is slightly above the level that corresponds to a serious injury risk. Then, a viscoelastic material was used instead of regular steel in the bulkhead design. After tuning the asymptotic modulus of elasticity from 200×10^9 N/m^2 to 200×10^3 N/m^2 and decay constant from 0.0001 to 1000, the final configuration identified from the parametric study had the following values: density equal to 6,000 kg/m^3, asymptotic modulus of elasticity equal to 800×10^6 N/m^2, and a decay constant equal to 0.0015. The Poisson's ratio did not vary and was set equal to 0.3.

Figure 4 summarizes the time histories of deformation of the upper torso relative to the pelvis, for the original configuration (bulkheads made of regular steel) and the final configuration. The values for the maximum spring compression and the associated DRI are also included in the figure. An improvement of 8.65% is observed in the DRI while achieving a 12.5% reduction in the mass of the structure (as mentioned earlier, the overall mass of the vehicle is kept at a constant value for all configurations).

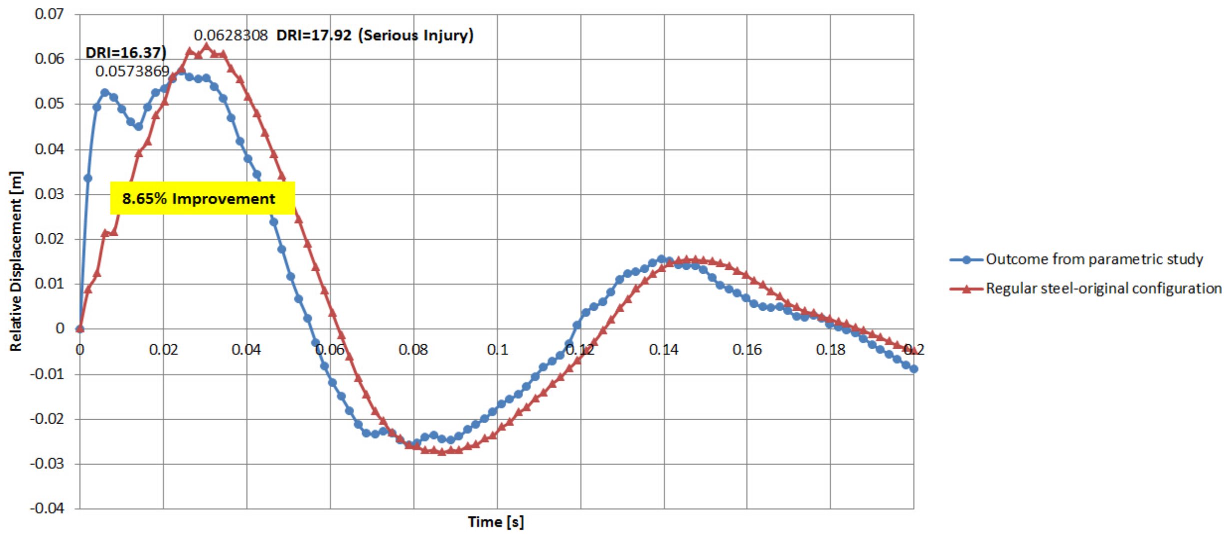


Figure 4. Time histories of deformation of the upper torso relative to the pelvis in the one-DOF DRI model

The parametric study for various decay constants under asymptotic modulus of elasticity of 800×10^{6} N/m^{2} are shown in Figure 5. It shows that neither a low decay constant (below 0.001) nor an excessive decay constant (above 10) will yield significant improvement in the DRI. This is because low damping has negligible ability for absorbing energy, and excessive damping causes a large phase lag that also has negative effects on decreasing the relative displacement. Based on this analysis, a value of 0.0015 was selected for the decay constant, and this was used in the final configuration for which results are presented in Figure 4.

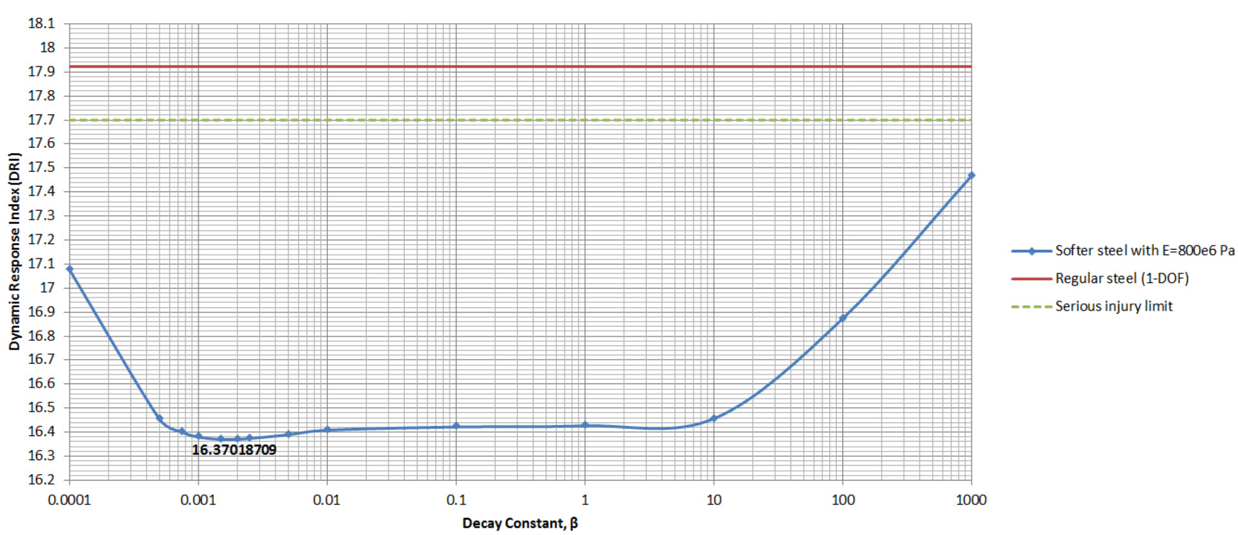


Figure 5. Parametric study for decay constant when asymptotic stiffness = 800×10^{6} N/m^{2}

3.2 Parametric study using Three-DOF model

In a similar manner, a parametric study was conducted involving multiple configurations with the three-DOF lumped parameter model used for evaluating the DRI (Figure 2(b)). This parametric study retains the value of 6,000 kg/m^3 for the density of the lower section of each bulkhead, based on the configuration identified by the earlier work. The asymptotic stiffness and the decay constant were varied as design parameters. For the final configuration, these two parameters were assigned values of 700×10^6 N/m^2 and 10, respectively.

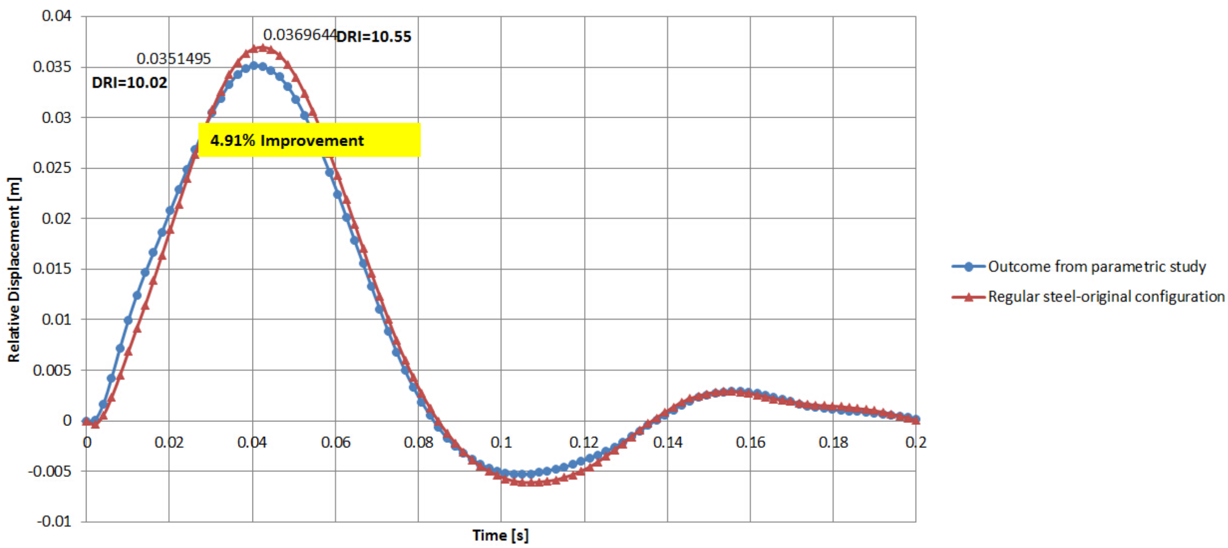


Figure 6. Time histories of deformation of the upper torso relative to the pelvis in the three-DOF lumped parameter DRI model; (b) Parametric study for decay constant when asymptotic stiffness = 700×10^6 N/m^2

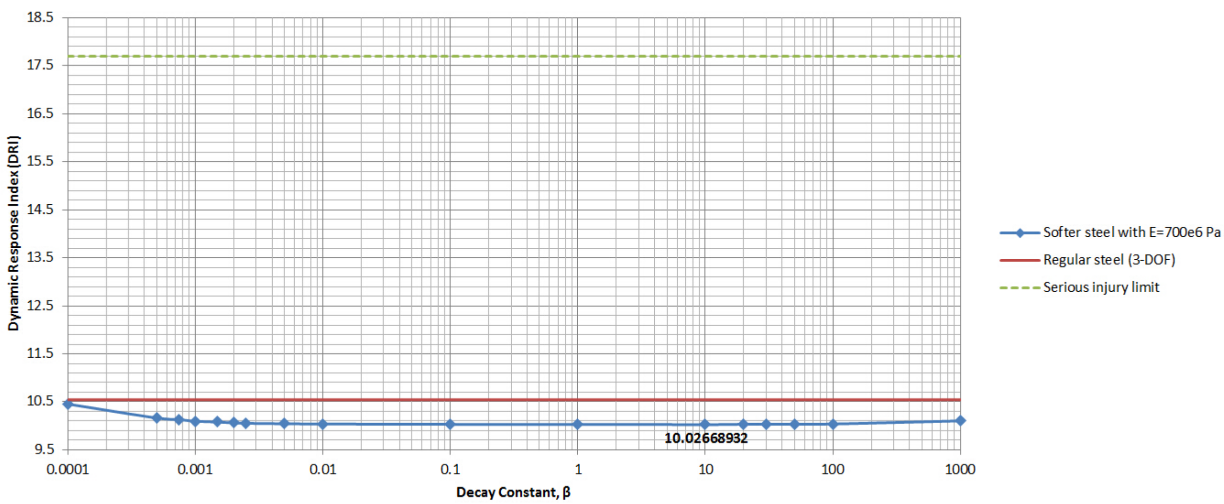


Figure 7. Parametric study for decay constant when asymptotic stiffness = 700×10^6 N/m^2

Figure 6 summarizes the time histories of deformation of the upper torso relative to the pelvis, for the original configuration and the final configuration. The values for the maximum spring compression and the associated DRI are also included in the figure. Actually, the DRI has already been improved significantly (a reduction of 41.2%) by adding the energy-absorbing floor and seat. The DRI improvement by the changes in the vehicle structure is 4.91% this time, however the reduction in the mass of the structure remains at 12.5%. The important aspect of this analysis is that the structural mass can be reduced while at the same time achieving a modest improvement in the DRI. The modest results are shown in Figure 7 for the parametric study with various decay constants under asymptotic modulus of elasticity of 700×10^6 N/m^2. The value of 10 was selected for the decay constant in the final configuration.

4. Conclusions

The results in this paper indicate that material properties can be tuned for changing the structural dynamic behavior of a vehicle in order to reduce the risk of occupant injuries while simultaneously maintaining or reducing the total weight. The intent was not to identify a specific material or design, but rather to demonstrate a process for identifying suitable stiffness, inertia, and damping characteristics of the various components. In addition to the material properties, the results depend on how and where the seat is connected to the vehicle as well as the relative stiffnesses and energy absorption characteristics of the floors and the seats. The selection process was driven by controlling and minimizing the energy that reaches the occupant from the blast. It was demonstrated that the weight of the tuned structure can be reduced while simultaneously creating various levels of improvement in blast protection as measured by the DRI metric.

ACRONYMS

DOF	Degree of Freedom
DRI	Dynamic Response Index
DTIC	Defense Technical Information Center
FEA/FEM	Finite Element Analysis/Model
MDOF	Multiple Degree of Freedom
SDOF	Single Degree of Freedom
TARDEC	Tank Automotive Research, Development and Engineering Center

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finding and conclusions or recommendations in this paper are those of the author(s) and do not necessarily reflect the views of the U.S. Army TACOM Life Cycle Command.

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Appendix A: Dynamic Response Index (DRI) – SDOF Mechanical Model

To evaluate the safety of vehicle designs, various metrics have been considered based on the prediction of dynamic response of occupants. For underbody blast events, there is a risk of injury to the lumbar region of the spine. The DRI, which is a standard occupant injury metric [10] for underbody blast simulation and testing, is used in this study as a measure of the structural performance with respect to survivability. The lumbar can be modeled as a single-DOF spring-mass-damper system, as shown in Figure A.1. [10-12]

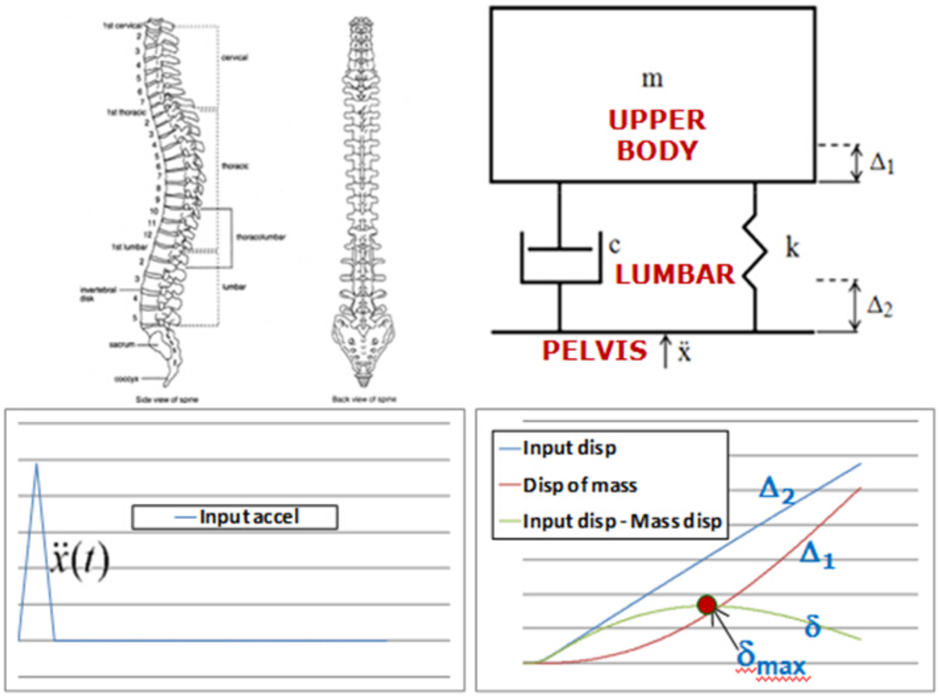


Figure A.1. Single-DOF spring-mass-damper system simulating human lumbar

For this study, the mass is 34.51kg, the spring coefficient is 9.66×10^4 N/m, and the damping coefficient is 818.1 N-sec/m. Therefore, the natural frequency and the damping ratio for the SDOF model are 52.9 rad/s and 0.224 respectively.

The governing equation is:

$$\frac{d^2\delta}{dt^2} + 2 * \zeta * \omega \frac{d\delta}{dt} + \omega^2 * \delta = \frac{d^2 z}{dt^2} \qquad \textbf{Eq. (A 1)}$$

where

$$\frac{d^2z}{dt^2} = \text{time-dependent shock acceleration (the excitation from the hull)}$$

$$\omega = \text{natural frequency} = \sqrt{\frac{k}{m}} = 52.9 \text{ rad/s}$$

$$\zeta = \text{damping ratio} = \frac{c}{2*\sqrt{m*k}} = 0.224$$

$\boldsymbol{\delta}$ = lumbar compression (relative displacement between pelvis and upper body) = $\Delta_2 - \Delta_1$

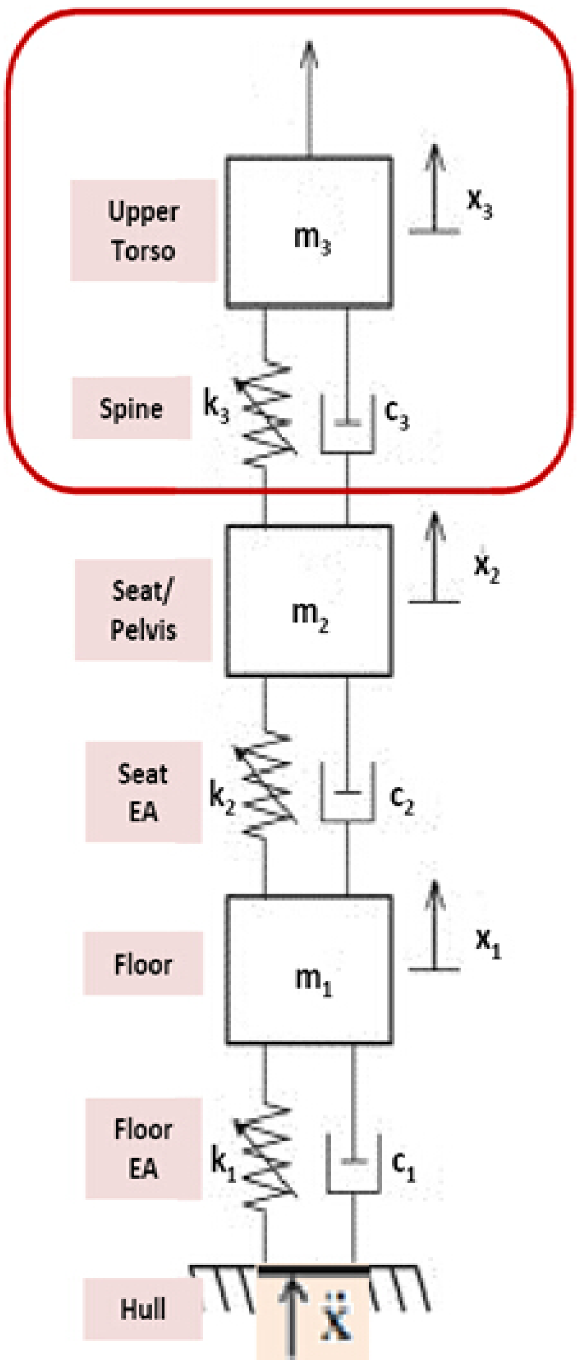
The DRI is the dynamic lumbar load during maximum lumbar compression ($\boldsymbol{\delta}$max) normalized by the static lumbar load due to weight of the upper torso. The ratio of these loads results in the following equation for the DRI [10]:

$$\text{DRI} = \frac{\omega^2}{g} * \boldsymbol{\delta}\text{max} \qquad \text{Eq. (A 2)}$$

The limiting DRI value is 17.7 with a 10% chance of serious injury which corresponds to a maximum lumbar compression of about 62 mm. Reducing DRI by absorbing under body destructive energy would keep the occupants safe in a blast event.

Appendix B: Dynamic Response Index (DRI) – Three-DOF Mechanical Model

In the three-DOF DRI model, [10] an energy-absorbing (EA) seat and an EA floor are mounted on the hull under the occupant's lumbar (SDOF model). Thus, two spring-mass-damper systems need to be included in the model as additional energy absorbers, as shown in Figure B.1. [10-12]



Assume: $z_3 = x_3 - x_2$
$z_2 = x_2 - x_1$
$z_1 = x_1 - x$

$$m_3\ddot{x}_3(t) = F_{spring3} + F_{damper3}$$

$$m_3\ddot{x}_3(t) = -k_3(x_3 - x_2) - c_3(\dot{x}_3 - \dot{x}_2)$$

$$m_3(\ddot{z}_3 + \ddot{x}_2) = -k_3 z_3 - c_3\dot{z}_3$$

$$\boldsymbol{m_3\ddot{z}_3(t) = -m_3\ddot{x}_2 - k_3 z_3 - c_3\dot{z}_3}$$

$$m_2\ddot{x}_2(t) = -F_{spring3} - F_{damper3} + F_{spring2} + F_{spring2}$$

$$m_2\ddot{x}_2(t) = k_3(x_3 - x_2) + c_3(\dot{x}_3 - \dot{x}_2) - k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1)$$

$$m_2(\ddot{z}_2 + \ddot{x}_1) = k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2$$

$$\boldsymbol{m_2\ddot{z}_2(t) = -m_2\ddot{x}_1 + k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2}$$

$$m_1\ddot{x}_1(t) = -F_{spring2} - F_{damper2} + F_{spring1} + F_{spring1}$$

$$m_1\ddot{x}_1(t) = k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) - k_1(x_1 - x) - c_1(\dot{x}_1 - \dot{x})$$

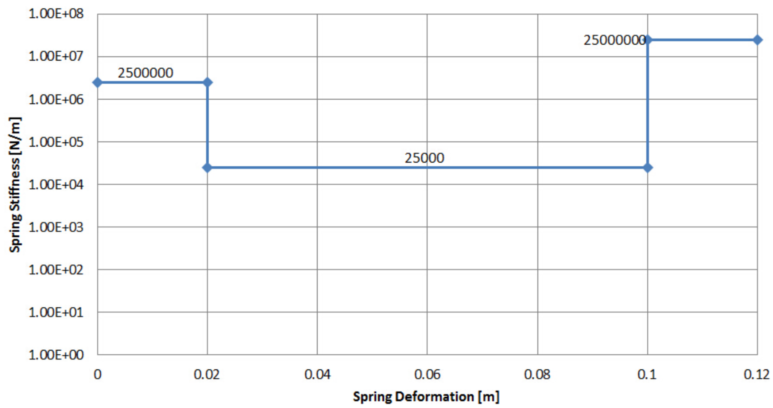
$$m_1(\ddot{z}_1 + \ddot{x}) = k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1$$

$$\boldsymbol{m_1\ddot{z}_1(t) = -m_1\ddot{x} + k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1}$$

Figure B.1. Three-DOF spring-mass-damper system simulating human lumbar, energy-absorbing seat, and energy-absorbing floor

The damping coefficient is set to a constant value of 9220 N*sec/m for both the seat and the floor. However, the spring is now piecewise-linear, with the spring stiffness values shown in Figure B.2(a) for the floor and Figure B.2(b) for the seat. Three regimes are defined for the spring stiffness: an initial stiffness regime, a low stiffness regime after yield, and a high stiffness regime after bottoming out.

(a)



(b)

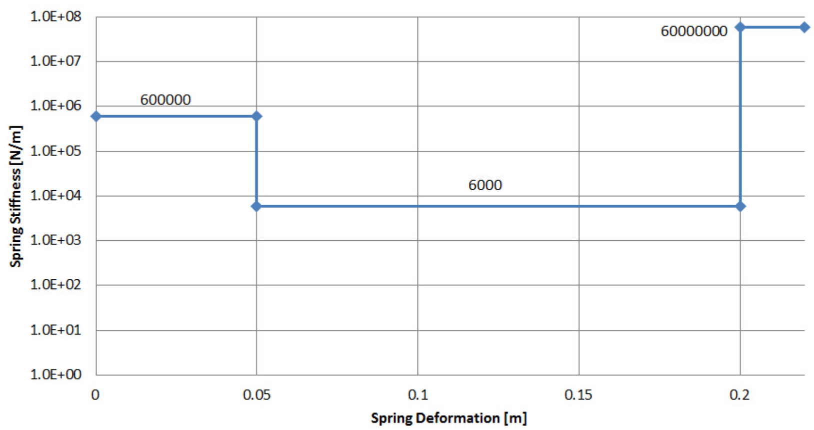


Figure B.2. Spring stiffness curves for (a) the floor and (b) the seat